

Wind Energy Resource Maps of Missouri

Prepared for:



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Department of
Natural Resources

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with financial assistance from U.S. DOE's Wind Powering America Program.

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March 31, 2005

DISCLAIMER

The maps described in this report were created by AWS Truewind using the MesoMap system and historical weather data. They have been validated by AWS Truewind, the National Renewable Energy Laboratory, and independent consultants, using available wind data. Although the maps are believed to represent an accurate overall picture of the wind energy resource, estimates at any location should be confirmed by measurement.

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EXECUTIVE SUMMARY

This report describes a wind-mapping project conducted by AWS Truewind for the Missouri Department of Natural Resources, Outreach and Assistance Center. Using the MesoMap system, AWS Truewind has produced maps of mean wind speed in Missouri for heights of 30, 50, 70, and 100 m above ground, as well as maps of wind power at 50 and 100 m. AWS has also produced data files of the predicted wind speed frequency distribution and speed and energy by direction. The maps and data files are provided on a CD with the ArcReader software, which will enable users to view, print, copy, and query the maps and wind rose data.

The MesoMap system consists of an integrated set of atmospheric simulation models, databases, and computers and storage systems. At the core of MesoMap is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model, which simulates the physics of the atmosphere. MASS is coupled to a simpler wind flow model, WindMap, which is used to refine the spatial resolution of MASS and account for localized effects of terrain and surface roughness. MASS simulates weather conditions over a region for 366 historical days randomly selected from a 15-year period. When the runs are finished, the results are input into WindMap. In this project, the MASS model was run on a grid spacing of 2.5 km and WindMap on a grid spacing of 200 m.

In collaboration with the National Renewable Energy Laboratory and independent consultants, AWS Truewind subsequently validated the wind maps using data from 42 stations. The data were first extrapolated to a height of 50 m. The predicted wind speeds are on average about 0.2 m/s higher than the observed/extrapolated speeds. We suspect, however, that this apparent positive bias reflects an underestimation of wind shear at several of the stations with short towers. After accounting for uncertainty in the data, we estimated the map standard error to be about 0.4 m/s, or 6.5% of the mean speed. The error margin is comparable to that obtained in other MesoMap projects.

While the maps depict the overall wind resource with reasonable accuracy, the validation revealed an area where MesoMap appears to have underestimated the wind resource. With the agreement of NREL, we adjusted the predicted wind speed and power of central eastern Missouri in the counties of St. Charles and St. Louis.

The wind maps indicate that the northwestern portion of the state, from the corner of Atchison County down to Kansas City, has the greatest abundance of windy land. The mean wind speed on many hills in this region is predicted to be 7.0-7.5 m/s at 70 m height. There are pockets of similar wind resource on relatively high elevations in the southwestern part of the state. In southeastern Missouri, dense forest cover and lower elevations substantially reduce the predicted wind speed and wind power.

1. INTRODUCTION

The Missouri Department of Natural Resources is interested in assessing the potential for wind energy development in Missouri and assisting developers in finding suitable sites for wind energy projects. Conventional field techniques of wind resource assessment can be time consuming, however, and often depend heavily on local meteorological expertise as well as the availability of reliable and representative wind measurements. Conventional wind flow models, on the other hand, have often proven inaccurate in complex wind regimes, and even in moderate terrain their accuracy can decline substantially with distance from the nearest available reference mast.

Mesoscale-microscale modeling techniques offer a solution to these challenges. By combining a sophisticated numerical weather model capable of simulating large-scale wind patterns with a microscale wind flow model responsive to local terrain and surface conditions, they enable the mapping of wind resources over large regions at much higher resolution and with much greater accuracy than has been possible in the past. In addition, they do not require surface wind data. While on-site measurements are still required to confirm the predicted wind resource at any particular location, mesoscale-microscale modeling can greatly reduce the time and cost to identify and evaluate potential wind project sites.

AWS Truewind (formerly known as TrueWind Solutions) has been the world leader in the development of mesoscale-microscale mapping techniques, having introduced the MesoMap system in the late 1990s. In the past five years, MesoMap has been applied in nearly 30 countries on four continents. In North America alone, MesoMap has been used to map over 30 US states and several provinces of Canada and states of Mexico.

The objective of the current project was to use MesoMap to create high-resolution wind resource maps of Missouri and to provide wind resource data in a format enabling the Missouri Department of Natural Resources to assess potential sites in a GIS. These objectives have been met. In the following sections, we describe the MesoMap system and mapping process in detail; how MesoMap was applied in this project; the validation process and results; the final wind maps and data files; and guidelines for the use of the maps.

2. DESCRIPTION OF THE MESOMAP SYSTEM

The MesoMap system has three main components: models, databases, and computer systems. These components are described below.

2.1. Models

At the core of the MesoMap system is MASS (Mesoscale Atmospheric Simulation System), a numerical weather model that has been developed over the past 20 years by AWS's partner MESO, Inc., both as a research tool and to provide commercial weather forecasting services. MASS simulates the fundamental physics of the atmosphere including conservation of mass, momentum, and energy, as well as the moisture phases,

and it contains a turbulent kinetic energy module that accounts for the effects of viscosity and thermal stability on wind shear. As a dynamical model, MASS simulates the evolution of atmospheric conditions in time steps as short as a few seconds. This creates great computational demands, especially when running at high resolution. Hence MASS is usually coupled to a simpler but much faster program, WindMap, a mass-conserving wind flow model. Depending on the size and complexity of the region and requirements of the client, WindMap is used to improve the spatial resolution of the MASS simulations to account for the local effects of terrain and surface roughness variations.

2.2. Data Sources

The MASS model uses a variety of online, global, geophysical and meteorological databases. The main meteorological inputs are reanalysis data, rawinsonde data, and land surface measurements. The reanalysis database – the most important – is a gridded historical weather data set produced by the US National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR). The data provide a snapshot of atmospheric conditions around the world at all levels of the atmosphere in intervals of six hours. Along with the rawinsonde and surface data, the reanalysis data establish the initial conditions as well as updated lateral boundary conditions for the MASS runs. The MASS model itself determines the evolution of atmospheric conditions within the region based on the interactions among different elements in the atmosphere and between the atmosphere and the surface. Because the reanalysis data are on a relatively coarse, 200 km grid, MASS is run in several nested grids of successively finer mesh size, each taking as input the output of the previous nest, until the desired grid scale is reached. This is to avoid generating noise at the boundaries that can result from large jumps in grid cell size. The outermost grid typically extends several thousand kilometers.

The main geophysical inputs are elevation, land cover, vegetation greenness (normalized differential vegetation index, or NDVI), soil moisture, and sea-surface temperatures. The global elevation data normally used by MesoMap were produced by the US Geological Survey in a gridded digital elevation model, or DEM, format from a variety of data sources.¹ The US Geological Survey, the University of Nebraska, and the European Commission's Joint Research Centre (JRC) produced the global land cover data in a cooperative project. The land cover classifications are derived from the interpretation of Advanced Very High Resolution Radiometer (AVHRR) data – the same data used to calculate the NDVI. The model translates both land cover and NDVI data into physical parameters such as surface roughness, albedo, and emissivity. The nominal spatial resolution of all of these data sets is 1 km. Thus, the standard output of the MesoMap system is a 1 km gridded wind map. However, much higher resolution maps can be produced where the necessary topographical and land cover data are available. In the United States, the resolution is typically 100 to 400 m.

¹The US Defense Department's high-resolution Digital Terrain Elevation Data set is the principal source for the global 1 km elevation. Gaps in the DTED data set were filled mainly by an analysis of 1:1,000,000 scale elevation contours in the Digital Chart of the World (now called VMAP).

2.3. Computer and Storage Systems

The MesoMap system requires a very powerful set of computers and storage systems to produce wind resource maps at a sufficiently high spatial resolution in a reasonable amount of time. To meet this need AWS Truewind has created a distributed processing network consisting of 94 Pentium II processors and 3 terabytes of hard disk storage. Since each day simulated by a processor is entirely independent of other days, a project can be run on this system up to 94 times faster than would be possible with any single processor. To put it another way, a typical MesoMap project that would take two years to run on a single processor can be completed in just one week.

2.4. The Mapping Process

The MesoMap system creates a wind resource map in several steps. First, the MASS model simulates weather conditions over 366 days selected from a 15-year period. The days are chosen through a stratified random sampling scheme so that each month and season is represented equally in the sample; only the year is randomized. Each simulation generates wind and other weather variables (including temperature, pressure, moisture, turbulent kinetic energy, and heat flux) in three dimensions throughout the model domain, and the information is stored at hourly intervals. When the runs are finished, the results are compiled into summary data files, which are then input into the WindMap program for the final mapping stage. The two main products are usually (1) color-coded maps of mean wind speed and power density at various heights above ground and (2) data files containing wind speed and direction frequency distribution parameters. The maps and data can then be compared with land and ocean surface wind measurements, and if significant discrepancies are observed, adjustments to the wind maps can be made.

2.5. Factors Affecting Accuracy

In our experience, the most important sources of error in the wind resource estimates produced by MesoMap are the following:

- Finite grid scale of the simulations
- Errors in assumed surface properties such as roughness
- Errors in the topographical and land cover data bases

The finite grid scale of the simulations results in a smoothing of terrain features such as mountains and valleys. For example, a mountain ridge that is 2000 m above sea level may appear to the model to be only 1600 m high. Where the flow is forced over the terrain, this smoothing can result in an underestimation of the mean wind speed or power at the ridge top. Where the mountains block the flow, on the other hand, the smoothing can result in an overestimation of the resource as the model understates the blocking effect. The problem of finite grid scale can be solved by increasing the spatial resolution of the simulations, but at a cost in computer processing and storage.

Errors in the topographical and land cover data can obviously affect wind resource estimates. While elevation data are usually reliable, errors in the size and location of terrain features nonetheless occur from time to time. Errors in the land cover data are more common, usually as a result of the misclassification of aerial or satellite imagery. It has been estimated that the global 1 km land cover database used in the MASS simulations is about 70% accurate. Where possible, more accurate and higher resolution land cover databases should be used in the WindMap stage of the mapping process to correct errors introduced in the MASS simulations. In the United States, we use a 30 m resolution, Landsat-derived, land cover database for this purpose.

Even if the land cover types are correctly identified, there is uncertainty in the surface properties that should be assigned to each type, and especially the vegetation height and roughness. The forest category, for example, may include many different varieties of trees with varying heights and density, leaf characteristics, and other features that affect surface roughness. Cropland may be virtually devoid of trees and buildings, or it may have many windbreaks. Uncertainties like these can be resolved only by acquiring more information about the area through aerial photography or field observation. However this is not practical when (as in this project) the area being mapped is very large.

3. IMPLEMENTATION OF MESOMAP FOR THIS PROJECT

The standard MesoMap configuration was used in this project. MASS was run on the following nested grids:

- First (outer) grid level: 30 km
- Second (intermediate) grid level: 8 km
- Third (inner) grid level: 2 km

The usual geophysical and meteorological inputs were used. The WindMap program adjusted the wind resource estimates to reflect local topography and surface roughness changes on a grid spacing of 200 m. For the topographical data, we used the National Elevation Dataset, a digital terrain model produced on a 30 m grid by the US Geological Survey (USGS). For the land cover, we used the National Land Cover Dataset, which is derived from Landsat imagery. It was also produced by the USGS on a 30 m grid.² Both data sets are of very high quality.

In converting from land cover to surface roughness, the roughness length values shown in Table 1 were assumed. We believe these values to be typical of conditions in states such as Missouri. However the actual roughness could vary a good deal within each class.

² Information on the National Land Cover Data set can be found at the following web address: <http://landcover.usgs.gov/national/landcover.html>. Information on the National Elevation Dataset (NED) can be found at <http://edcwww.cr.usgs.gov/products/elevation/ned.html>.

Table 1. Range of Surface Roughness Values for Leading Land Cover Types

Description	Roughness (m)
Perennial Snow and Ice	0.003
Cropland	0.03
Grasslands/Herbaceous	0.05
Shrubland	0.07
Deciduous Forest	0.9
Evergreen and Mixed Forest	1.125
Wetland	0.66
Residential and Urban	0.3

The roughness is not the only surface property with a direct effect on near-surface wind speeds. Where there is dense vegetation the wind can skim along the vegetation canopy, thereby displacing the flow above the ground and reducing the speed observed at a fixed height above ground. The displacement height is defined as the height at which the wind speed becomes zero in the logarithmic shear formula. The shear formula is as follows:

$$\frac{v_2}{v_1} = \frac{\ln\left(\frac{z_2 - d}{z_0}\right)}{\ln\left(\frac{z_1 - d}{z_0}\right)}$$

Here, d is the displacement height, z_1 and z_2 are two different heights at which the speed v is measured, and z_0 is the surface roughness (generally much less than z_2 and z_1). Note that according to this formula, when $z_2 = d + z_0$, $v_2 = 0$.

The displacement height is usually estimated to be about two-thirds to three-fourths the maximum vegetation height. For this project, we assumed that the displacement height was 10 times the surface roughness length, which was in turn defined to be approximately 7.5% of the vegetation height. For deciduous forests with a roughness length of 0.9 m, this resulted in a displacement height of 9 m.

The effect of displacement height is to reduce the wind speed observed near the ground and to increase the apparent wind shear measured with respect to ground level. It can also reduce the wind speed measured in small clearings, since the ground appears to be in a “hole” at a depth d below the vegetation canopy. The impact of this hole on wind speed diminishes as the clearing becomes large enough for the flow to reach equilibrium with the new effective ground height. As a rule of thumb, the clearing width should be at least 20 times the displacement height for the effect to be negligible at the center of the clearing, but under some conditions the minimum width should be even larger.

4. VALIDATION

The wind resource maps were initially produced without any reference to surface wind measurements. AWS and NREL then validated the wind maps by comparing the predicted speed against data from 42 stations. Consulting meteorologist Richard L. Simon contributed insights to the analysis. The data set included 28 airports, number of other automated weather stations (RAWS), four 20 m masts from the Missouri Anemometer Loan Program, two 40 m towers installed by AWS Truewind, and one 50 m tower installed by the Iowa Wind Energy Institute (IWEI).

The validation was carried out in the following steps:

1. Station locations were verified and adjusted, if necessary, by comparing the quoted elevations and station descriptions against the elevation and land cover maps. Where there was an obvious error in position, the station was moved to the nearest point with the correct elevation and surface characteristics.
2. The observed mean speed and power were extrapolated to a common reference height of 50 m using the power law. Only the three tallest towers provided wind shear data; for the rest, the shear had to be estimated from the available information about each site. Assumed shear exponents ranged from 0.14 at large airports to 0.25 at relatively sheltered sites in forested terrain.³
3. The error margin for each data point was then estimated as a function of two factors: the tower height and the number of years of measurement. The tower height enters the equation because of uncertainty in the wind shear. We assumed an error margin in the shear exponent of 0.05, reflecting significant uncertainty in the ground cover, tree height, buildings, and other factors. The number of years of data affects the uncertainty because winds recorded over a short period may not be representative of long-term conditions. A rule of thumb is that a mean speed based on one year of data will be within 10% of the true long-term mean with 90% confidence. This translates into a standard error of 6% for one year of data. We assumed that the annual mean varies randomly according to a normal distribution, and thus the error margin varies inversely with the square root of the number of years. An additional uncertainty of 3% was added to account for possible variations in the characteristics of anemometers and data loggers.
4. The various uncertainties were then combined in a least-squares sum as follows:

$$(1) \ e = \sqrt{0.03^2 + \left(\left(\frac{50}{H} \right)^{0.05} - 1 \right)^2 + \left(\frac{0.06}{\sqrt{N}} \right)^2}$$

³ The power shear exponent is assumed to be $3(\alpha - 0.02)$, where α is the speed shear exponent. The reason for the reduction in effective shear, compared to assuming that the power goes strictly as the cube of the speed, is that the speed frequency distribution tends to become narrower with height above ground because the shear is often higher under light wind conditions.

where H is the height of the anemometer, and N the number of years of measurement. The uncertainty in power (in percentage terms) is assumed to be three times the uncertainty in speed, since the power varies as the cube of the speed.

5. Next, the predicted and measured/extrapolated speed and power were compared, and the map bias (map speed or power minus measured/extrapolated speed or power) was calculated for each point. Four stations were dropped at this point because of what appeared to be unreasonably low wind speeds, suggesting the sites might be sheltered by trees or buildings.

Table 2 summarizes the results. The key finding is that the standard deviation of the biases in speed and power were 0.37 m/s (6.5% of the average observed speed) and 44 W/m² (20% of the average observed power), respectively. The wind power discrepancy is larger than the wind speed discrepancy in percentage terms because the power varies as the cube of the speed.

Table 2. Validation

	Number of Stations	Mean Bias	Standard Deviation of the Biases	Model Error
Speed	38	0.23 m/s (4.0%)	0.37 m/s (6.5%)	NA
Power	38	-10 W/m ² (-4.5%)	44 W/m ² (20%)	NA

The standard deviation of the biases reflects errors both in the model and the data, and thus it tends to overstate the error of the maps alone. The model error is estimated by subtracting (in a least-squares sense) the standard error of the data (e_{DATA}) from the total RMS discrepancy (e_{TOTAL}):

$$(2) \ e_{MODEL} \approx \sqrt{e_{TOTAL}^2 - e_{DATA}^2}$$

This equation assumes that the errors in the model and data are random, normally distributed, and independent of one another. Applying this equation to the present case, however, the result is undefined (“NA”) for both power and speed. This is because the uncertainty in the data is, on average, comparable to the map bias. The relatively high uncertainty in the data reflects the number of stations with short towers (below 10 m in height) and short periods of record (less than one year).

The scatter plots in Figure 1 compare the predicted and measured-extrapolated wind speed and power at 50 m height. The linear trend lines, which are forced through the origin, confirm that the map speeds are about 4% higher than the observed/extrapolated speeds, on average, while the map power shows the opposite bias.

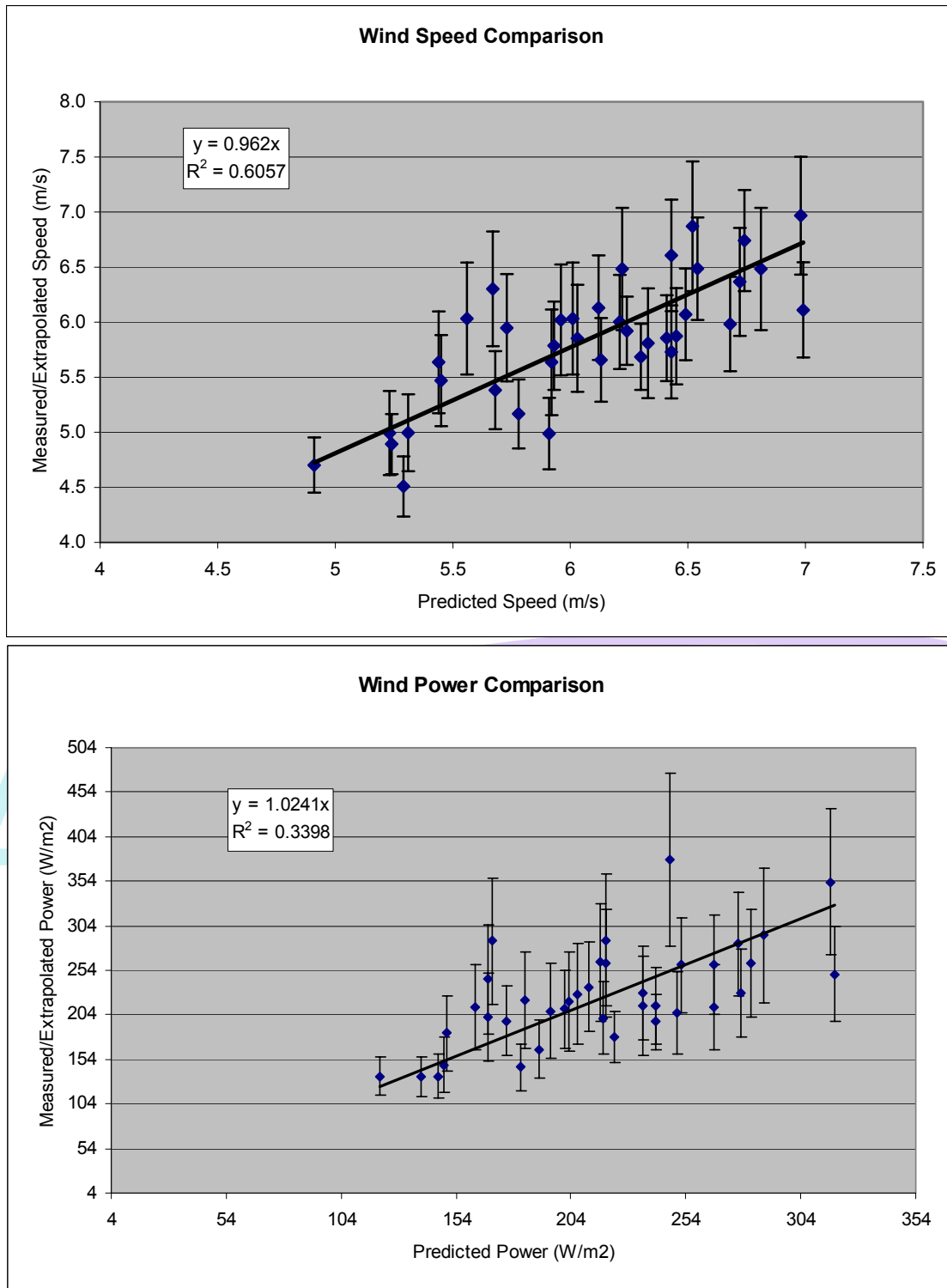


Figure 1. Scatter plots of predicted and measured wind speeds for 38 stations in Missouri at 50 m (top), and the same for wind power at 38 stations (bottom). The error bars reflect period of record, tower height, and anemometer sensitivity, as described in the text. The trend lines are forced through the origin.

After reviewing the validation results, NREL recommended moderate adjustments in speed and power one region of the state. The speed was increased by 5% in eastern Missouri in the counties of St. Charles and St. Louis, and the power was increased by about 30%.

5. WIND MAPS

The accompanying maps, which incorporate the adjustments described in the previous section, show the predicted mean annual wind speed in Missouri at heights of 30, 50, 70, and 100 m; maps of mean annual wind power at 50 and 100 m are also provided. In the past, the conventional wisdom was that commercial wind projects required a mean speed of at least 7 m/s, or a mean power of at least 400 W/m² (NREL class 4), at 50 m. In the last several years, however, wind projects have been built in areas with a more moderate wind resource using turbines mounted on taller towers and designed to operate at lower wind speeds. The hub heights of modern, large turbines typically range from 65 to 80 m, and some models reach 100 m.

Small turbines are designed to operate at lower wind speeds, and may be useful at mean speeds at 30 m height as low as 5-6 m/s (approximately NREL class 2 to 3).

The wind maps show that the best wind resource in Missouri is found in the northwestern portion of the state, from the corner of Atchison County down to Kansas City. The mean wind speed on many exposed hills in this region is predicted to be 7.0-7.5 m/s at 70 m, and may exceed 8 m/s in a few locations at 100 m. The predicted wind power density at 100 m is 400-500 W/m² in most areas and exceeds 500 W/m² at the best locations. According to NREL's power classification scheme, which is based on the power at 50 m, these areas are no better than class 3. Both the speed and power are predicted to increase substantially with height, however, resulting in potentially useful wind resource at the hub height of a modern, large turbine. The increase in speed and power with height, or wind shear, reflects the influence primarily of thermally stable conditions at night, which allows high winds aloft to come much closer to the surface than they do during the day.

Pockets of potentially attractive wind resource appear in other parts of the state as well, such as the southwestern corner, where the terrain is elevated, and in relatively open and higher elevations of north-central Missouri. The wind speeds at 70 m in these regions reach just over 7.0 m/s, and range from 7.5-8 m/s at 100 m, whereas the wind power at 100 m typically exceeds 400 W/m².

The wind resource is generally lowest in the southeastern portion of Missouri, where the predicted wind speeds even at 100 m do not exceed 7 m/s. The main reason for the lower wind resource in this area compared to the northern and western parts of the state is tree cover: southeastern Missouri is much more forested than the northern and western Missouri. Trees exert friction on the lower atmosphere, thereby reducing the wind speed.

Topography also plays a role. All other things being equal, hilltops usually have a better resource than valleys and plains. The elevated areas of Missouri in the southwestern and

northwestern parts of the state typically have higher wind speeds than low-lying areas along the Missouri River Valley in central and southeastern Missouri.

It should be stressed that the mean wind speed at any particular location may depart substantially from the predicted values, especially where the elevation, exposure, or surface roughness differs from that assumed by the model, or where the model scale is inadequate to resolve significant features of the terrain. In addition, despite the adjustments we have made, there is no guarantee that the revised wind map is any more accurate, in areas where no data was available, than the original map.

6. GUIDELINES FOR USE OF THE MAPS

The following are guidelines for interpreting and adjusting the wind speed estimates in the maps, to be used in conjunction with the accompanying ArcReader CD. The ArcReader CD allows users to obtain the “exact” wind speed value at any point, and it provides the elevation and surface roughness data used by the model, which are needed to apply the adjustment formulas given below.

1. The maps assume that all locations are free of obstacles that could disrupt or impede the wind flow. “Obstacle” does not apply to trees if they are common to the landscape, since their effects are already accounted for in the predicted speed. However, a large outcropping of rock or a house would pose an obstacle, as would a nearby shelterbelt of trees or a building in an otherwise open landscape. As a rule of thumb, the effect of such obstacles extends to a height of about twice the obstacle height and to a distance downwind of 10-20 times the obstacle height.
2. Generally speaking, points that lie above the average elevation within a 200×200 m grid cell will be somewhat windier than points that lie below it. A rule of thumb is that every 100 m increase in elevation will raise the mean speed by about 0.5 m/s. This formula is most applicable to small, isolated hills or ridges in flat terrain.
3. The mean wind speed at a location could be affected by the roughness of the land surface – determined mainly by vegetation cover and buildings – up to several kilometers away. If the roughness is much lower than that assumed by the model, the mean wind speed could be higher. Typical values of roughness range from 0.01 m in open, flat ground without significant trees or shrubs, to 0.1 m in land with few trees but some smaller shrubs, to 1 m or more for areas with many trees. These values are only indirectly related to the size of the vegetation.

The following equation provides an approximate speed adjustment for differences in surface roughness in the direction of the wind:

$$\frac{v_2}{v_1} \approx \frac{\log\left(\frac{300-d}{z_{01}}\right)}{\log\left(\frac{h-d}{z_{01}}\right)} \times \frac{\log\left(\frac{h-d}{z_{02}}\right)}{\log\left(\frac{300-d}{z_{02}}\right)}$$

v_1 and v_2 are the original and adjusted wind speeds at height h (in meters above ground level); z_{01} and z_{02} are the model and actual surface roughness values (in meters); and d_1 and d_2 are the corresponding displacement heights. (This equation assumes the wind is unaffected by localized roughness changes above a height of 300 m.)

As an example, suppose the surface roughness assumed by the model was 0.2 m, and the displacement 2 m, whereas the true roughness is 0.75 m and displacement 7.5 m. For $h = 50$ m, the above formula gives

$$\frac{v_2}{v_1} \approx \frac{\log\left(\frac{300-2}{0.2}\right)}{\log\left(\frac{50-2}{0.2}\right)} \times \frac{\log\left(\frac{50-7.5}{0.75}\right)}{\log\left(\frac{300-7.5}{0.75}\right)} = 0.90$$

This shows that the predicted wind speed should be reduced by about 10%.

This formula assumes that the wind is in equilibrium with the new surface roughness above the height of interest (in this case 50 m). When going from high roughness to low roughness (such as from forested to open land), the clearing should be at least 1000 m wide for the benefit of the lower roughness to be fully realized. However, when going from low to high roughness, the reduction in wind speed may be felt over a much shorter distance. For this and other reasons, the formula should be applied with care.

AWS Truewind